Reliability Assessment and Protection Coordination of Low-Voltage Electrical Distribution Systems in Nigerian Manufacturing Facilities

Abimbola Olamide Ayotomiwa[1,*], Toheeb Oluwaseun Adamolekun[1]

[1]Department of Electrical and Computer Engineering, North Carolina A&T State University, Greensboro, NC, USA

* Corresponding author: Abimbola Olamide Ayotomiwa, bimbolahan@gmail.com

Abstract

Reliable electrical infrastructure is indispensable to industrial productivity, operational safety, and sustainable manufacturing in Nigeria. This review examines the design and performance of low-voltage distribution networks, with particular emphasis on reliability assessment, electrical fault behaviour, protective-device coordination, and power quality. It aims to identify major sources of operational vulnerability and establish practical priorities for improving continuity of supply within manufacturing facilities.

A structured narrative synthesis of published engineering literature and applicable technical standards, restricted to sources published through 2020, was undertaken. The discussion integrates distribution architectures, interruption and availability indicators, component failure analysis, probabilistic assessment methods, short-circuit studies, and protection selectivity principles. Particular consideration is given to facilities combining utility supply with standby generation and renewable energy resources.

The synthesis identifies several recurrent reliability concerns: ageing or inadequately maintained equipment, overloaded feeders, insulation deterioration, voltage disturbances, and protection arrangements that may disconnect healthy production circuits during localised faults. It further shows that alternative electricity sources can modify available fault currents, making coordination assessments under distinct operating configurations essential. Reliability indicators and condition monitoring provide complementary means of prioritising interventions, although limited facility-specific failure data constrain the strength of conclusions about Nigerian manufacturing performance.

The review recommends periodic electrical audits, updated short-circuit and discrimination studies, risk-based preventive maintenance, power quality monitoring, and selective investment in redundancy and critical-load support. Consistent fault reporting, workforce development, and field-based validation are also necessary. Ultimately, more dependable industrial distribution requires integrating sound network design with verified protection settings and evidence-led maintenance decisions, rather than relying solely on additional generation capacity across diverse Nigerian industrial settings.

Keywords: Low-voltage distribution systems; Electrical reliability assessment; Protection coordination; Industrial fault analysis; Power quality; Nigerian manufacturing facilities.

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1. INTRODUCTION

1.1 Background of Industrial Electrical Distribution Systems

Industrial electrical distribution systems represent essential infrastructure supporting manufacturing operations by delivering electrical energy to production machinery, automated equipment, lighting, ventilation, and auxiliary facilities. These systems comprise interconnected transformers, switchgear, distribution boards, conductors, and protective devices that facilitate controlled electricity delivery from utility networks or on-site generation sources. In manufacturing installations, low-voltage distribution commonly operates at nominal voltages of 400/230 V or 415/240 V, depending on applicable supply specifications. Effective system design must accommodate fluctuating electrical loads, equipment starting currents, short-circuit conditions, and operational safety requirements. International engineering standards establish fundamental requirements for circuit protection, fault interruption, and protective coordination (IEC, 2016).

The operational importance of electrical distribution extends beyond energy delivery because contemporary manufacturing increasingly depends on automated production systems, programmable controllers, variable-frequency drives, and electrically driven machinery. These technologies require stable voltage conditions and dependable power availability to maintain operational efficiency. Electrical disturbances, particularly voltage sags, can interrupt sensitive equipment, disrupt automated processes, and necessitate costly production restarts. Consequently, distribution-system performance must incorporate power-quality considerations alongside conventional electrical capacity requirements (Costa et al., 2019).

Reliability constitutes another fundamental requirement, encompassing supply continuity, equipment availability, fault tolerance, and restoration capability. Within Nigerian manufacturing environments, inconsistent electricity supply frequently contributes to production interruptions, equipment deterioration, and increased operating expenditure. Empirical investigations demonstrate that electricity disruptions adversely affect manufacturing productivity, particularly among smaller enterprises with limited alternative power resources (Moyo, 2012). These challenges establish electrical reliability as an important determinant of industrial competitiveness and operational sustainability.

Distribution-network configuration significantly influences fault exposure and supply continuity. Radial arrangements remain prevalent because of their operational simplicity and relatively economical installation. However, individual feeder failures may interrupt substantial production activities where alternative supply pathways are unavailable. Effective protection coordination therefore requires appropriate selection and discrimination of protective devices to isolate faulty circuits while maintaining electricity delivery to unaffected equipment. Integrating distributed generation introduces further complications because fault-current characteristics may change according to network configuration and operating conditions (Brearley & Prabu, 2017).

Alternative energy integration has consequently become increasingly relevant to Nigerian manufacturing facilities seeking improved supply reliability. Photovoltaic systems, battery storage, and standby generators provide opportunities for reducing dependence on unreliable utility electricity. Nevertheless, their successful integration requires compatible distribution infrastructure, coordinated protection, and effective energy management (Sunday & Omoegun, 2018). Intelligent fault-detection approaches further demonstrate potential for improving protection performance under variable generation conditions (Bukhari et al., 2018).

Continuous electrical monitoring additionally supports reliability assessment through systematic measurement of voltage variations, current fluctuations, and power-quality disturbances. Smart sensing technologies facilitate early identification of abnormal operating conditions and provide information for maintenance decisions (Morales-Velazquez et al., 2017). Adaptive protection arrangements similarly support dependable fault management during transitions between grid-connected and autonomous operation (Habib et al., 2017).

Finally, structured maintenance planning remains essential for sustaining distribution-system performance. Evidence from South African power infrastructure highlights the importance of preventive maintenance, outage coordination, and operational preparedness in improving equipment availability (Hlophe & Visser, 2018). Integrating these principles with appropriate protection design and monitoring practices can strengthen electrical reliability and manufacturing continuity in Nigeria.

1.2 Electrical Reliability Challenges in Nigerian Manufacturing

Electrical reliability remains a significant challenge within Nigeria’s manufacturing sector, where uninterrupted production depends on dependable utility supply and properly maintained distribution

infrastructure. Frequent outages, voltage fluctuations, inadequate network maintenance, and limited supply redundancy contribute to operational disruptions and increased production costs. Small and medium-sized manufacturers are particularly vulnerable because financial constraints restrict investment in alternative electricity sources and resilient infrastructure. Studies indicate that persistent electricity interruptions undermine industrial productivity, increase operating expenditure, and weaken manufacturing competitiveness (Akuru & Okoro, 2014).

Beyond utility supply limitations, internal electrical installations frequently experience deteriorating insulation, overloaded feeders, ageing switchgear, and inadequate protective-device coordination. These deficiencies increase exposure to short circuits, earth faults, and unintended equipment disconnections. Poorly coordinated protection systems may allow localised faults to interrupt extensive production areas, demonstrating the importance of selective fault isolation and systematic maintenance. Evidence from Nigerian manufacturing enterprises further establishes the relationship between electricity service quality and operational performance (Muhammed, Abdulraheem & Yusuf, 2017).

Standby generators provide partial mitigation against unreliable grid electricity, although insufficient generating capacity, improper switching arrangements, and maintenance deficiencies can limit their effectiveness (Oseni & Pollitt, 2015). International evidence similarly demonstrates that electricity shortages adversely affect manufacturing revenues, production efficiency, and resource allocation, particularly among enterprises lacking dependable backup arrangements (Allcott et al., 2016; Fisher-Vanden, Mansur & Wang, 2015).

Across sub-Saharan Africa, unreliable electricity infrastructure continues to constrain economic productivity and industrial development (Andersen & Dalgaard, 2013). Addressing these challenges within Nigerian manufacturing requires coordinated protection systems, preventive maintenance, systematic fault investigations, and appropriate distribution redundancy. Strengthening these capabilities can minimise unnecessary disconnections, improve fault recovery, and sustain essential manufacturing operations under abnormal electrical conditions.

1.3 Significance of Effective Electrical Protection Coordination

Effective electrical protection coordination is fundamental to maintaining operational reliability, equipment safety, and production continuity within low-voltage distribution systems serving Nigerian manufacturing facilities. Protection coordination involves establishing appropriate operating

relationships among circuit breakers, fuses, and protective relays to ensure that electrical faults are cleared selectively without unnecessarily disconnecting healthy circuits. Its importance is particularly evident in industrial installations where interconnected production equipment depends on continuous electrical supply. Nigerian research on radially connected networks demonstrates that inadequate relay coordination can cause simultaneous upstream and downstream tripping, extending interruptions beyond the affected feeder and reducing overall system reliability (Onah, 2012).

Within manufacturing environments, properly coordinated protective devices reduce the consequences of short circuits, earth faults, and abnormal overcurrents by limiting the duration and extent of electrical disturbances. Protection selectivity requires careful evaluation of prospective fault currents, device operating characteristics, and coordination intervals. Research on distribution networks containing overhead conductors and underground cables demonstrates that optimising overcurrent relay settings can minimise fault-clearing times while preserving appropriate relationships between primary and backup protection (Khond & Dhomane, 2019).

The increasing adoption of alternative electricity sources further strengthens the significance of protection coordination. Nigerian manufacturing facilities frequently incorporate standby generators or renewable energy systems to supplement unreliable utility supplies. However, multiple sources can alter fault-current contributions and complicate conventional protection arrangements. An investigation of the Trans Amadi distribution network in Port Harcourt demonstrated that distributed generation can disrupt existing protective-device coordination, highlighting the need to reassess protection settings when network configurations change (Osabohien & Uhunmwangho, 2018).

International developments also emphasise the importance of adaptable protection arrangements. Research examining meshed distribution networks established that dual-setting directional overcurrent relays can improve coordination and reduce operating times under changing fault-current directions. Such approaches provide useful engineering principles for industrial facilities incorporating interconnected feeders and distributed generation (Zeineldin et al., 2015).

Protection coordination additionally depends on sustained equipment integrity, regular testing, and systematic maintenance. Evidence from South African electrical substations highlights the operational risks associated with ageing protective equipment and insufficient maintenance, emphasising the importance of modernisation and structured maintenance programmes (Nko & Chowdhury, 2016). For Nigerian manufacturers, effective coordination therefore requires verified short-circuit calculations,

appropriate protective-device selection, periodic setting reviews, and documented maintenance procedures to minimise avoidable production interruptions and electrical equipment damage.

1.4 Review Objectives, Scope, and Research Gaps

This review critically examines the reliability characteristics and protection coordination requirements of low-voltage electrical distribution systems in Nigerian manufacturing facilities. Its primary objective is to evaluate the technical and operational factors influencing electrical supply continuity, fault detection, protective-device selectivity, and equipment availability. Particular attention is given to identifying engineering practices that minimise unplanned interruptions, improve fault isolation, and strengthen the operational resilience of industrial electrical infrastructure.

The review encompasses industrial distribution architectures, reliability assessment methodologies, electrical fault characteristics, protective-device selection, and power quality disturbances. It considers the interaction between utility supplies, standby generators, renewable energy installations, and internal distribution networks, recognising that multiple electricity sources introduce additional complexities in fault-current behaviour and protection coordination. Emphasis is placed on practical engineering considerations relevant to manufacturing environments experiencing fluctuating electrical demand, infrastructure deterioration, and constrained maintenance resources.

Despite established advances in power-system reliability and protection engineering, significant research gaps remain concerning their application within Nigerian manufacturing facilities. Existing investigations frequently emphasise national electricity supply deficiencies, generation capacity, and economic consequences, with comparatively limited attention to facility-level distribution reliability, protective-device discrimination, and systematic fault analysis. Furthermore, insufficient facility-specific empirical evidence constrains the assessment of equipment failure patterns, protection misoperations, and maintenance effectiveness.

Accordingly, this review seeks to establish a coherent technical foundation for identifying reliability deficiencies, evaluating protection coordination practices, and proposing context-appropriate improvements. It also highlights priorities for future empirical investigations, including industrial fault-data collection, coordination studies, and performance-based reliability assessments across Nigerian manufacturing installations.

2. LOW-VOLTAGE DISTRIBUTION ARCHITECTURES IN MANUFACTURING FACILITIES

Low-voltage electrical distribution architectures play a fundamental role in determining operational reliability, electrical safety, and energy efficiency within manufacturing facilities. These systems comprise transformers, switchboards, busbars, distribution panels, feeder circuits, and protective devices configured to deliver electricity to industrial equipment. Architectural selection influences power losses, fault-current behaviour, maintenance accessibility, and supply continuity. Common configurations include radial, ring, interconnected, and redundant networks, each presenting distinct advantages concerning installation costs, operational flexibility, and reliability. Distribution topology therefore requires careful evaluation against industrial load characteristics and operational requirements (Prabhala et al., 2018).

Radial distribution networks remain prevalent in manufacturing installations because their straightforward arrangements simplify installation, maintenance, fault identification, and protective-device coordination. However, dependence on individual supply pathways increases vulnerability to feeder failures, potentially disconnecting downstream production equipment. Ring and interconnected architectures offer alternative supply routes and improved operational flexibility but introduce additional switching and protection complexities. Comparative assessments of microgrid configurations emphasise balancing investment requirements, fault tolerance, and operational adaptability when selecting appropriate distribution arrangements (Kumar, Agarwal & Agarwal, 2019).

Within Nigerian manufacturing environments, unreliable utility electricity necessitates distribution architectures capable of accommodating alternative energy sources. Diesel generators, photovoltaic installations, and battery storage systems provide supplementary electricity supplies that can improve production continuity. Nevertheless, successful integration requires appropriate generation capacity, load prioritisation, voltage regulation, and coordinated switching arrangements. Nigerian investigations of hybrid renewable energy configurations demonstrate opportunities for improving electricity availability while managing technical and economic constraints (Sofimieari, Mustafa & Obite, 2019).

Hybrid distribution systems additionally support coordinated energy allocation across conventional and renewable generation sources. Appropriate power management can reduce unnecessary generator operation, minimise electrical losses, and maintain supply to essential industrial loads. Research on

hybrid solar installations highlights the importance of load optimisation and systematic energy management in improving decentralised electricity performance (Sunday & Omoegun, 2019).

The integration of alternating-current and direct-current infrastructure introduces further design considerations. Hybrid AC/DC networks require suitable converters, interconnection arrangements, and coordinated power-flow control to accommodate renewable generation and energy storage. Load-flow assessments consequently support evaluation of voltage stability, power distribution, and operating constraints under changing network conditions (Khan et al., 2018). Bidirectional converters further facilitate controlled energy exchange between interconnected electrical subsystems (Salas-Puente et al., 2018).

Nevertheless, renewable generation variability and fluctuating manufacturing demand necessitate robust energy management and uncertainty assessment. Research emphasises optimisation strategies for maintaining dependable operation within interconnected hybrid networks (Pourbehzadi et al., 2019).

African investigations further demonstrate the importance of appropriate conductor sizing, generation planning, storage capacity, and distribution flexibility (Bokanga et al., 2014; Motjoadi, Bokoro & Onibonoje, 2020). Accordingly, Nigerian manufacturing facilities require context-sensitive architectures that integrate supply resilience, selective fault isolation, maintainability, and efficient energy management to sustain industrial production under variable electrical operating conditions.

3. RELIABILITY ASSESSMENT METHODS AND PERFORMANCE INDICATORS

Reliability assessment provides a systematic framework for determining the ability of low-voltage electrical distribution systems to maintain satisfactory service under normal operating conditions and foreseeable equipment failures. Within Nigerian manufacturing facilities, reliability evaluation requires consideration of component failure probabilities, outage frequencies, restoration durations, and the operational consequences of interrupted electricity supply. Assessment methodologies generally incorporate historical failure analysis, analytical reliability modelling, and probabilistic simulation. The selection of an appropriate technique depends on network complexity, data availability, redundancy arrangements, and the presence of distributed energy resources. A comprehensive review of modern distribution networks establishes that reliability modelling must accommodate evolving network architectures, automated protection systems, and operational uncertainties to produce representative performance evaluations (Escalera, Hayes & Prodanović, 2018).

Quantitative reliability assessment commonly employs the System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), and Average Service Availability Index (ASAI). These indicators measure interruption frequency, accumulated outage duration, average restoration time, and service availability, respectively. For industrial installations, their application requires appropriate adaptation because production equipment and critical feeders represent distinct operational loads rather than conventional utility customers. Nigerian investigations involving several distribution networks demonstrate the usefulness of sensitivity analysis for identifying variations in reliability indices and determining feeders requiring operational improvement (Ajenikoko & Oyedele, 2019).

Historical outage analysis provides an important empirical foundation for evaluating distribution-system performance. Maintenance records, switching logs, equipment failure reports, and interruption histories can establish component failure rates and average restoration durations. Investigations of electricity distribution substations in Port Harcourt demonstrate the application of analytical methods and electrical-system simulation to estimate interruption indices and compare network reliability characteristics. Such approaches are relevant to manufacturing facilities where historical operational records can support the identification of vulnerable distribution components (Oreke & Idoniboyeobu, 2017).

Reliability evaluation also requires consideration of component-level performance indicators, particularly mean time between failures (MTBF), mean time to repair (MTTR), and operational availability. These measures establish the relationship between equipment failure behaviour and restoration requirements. Probabilistic modelling enables engineers to examine uncertainties in component operating conditions rather than relying exclusively on deterministic assumptions. Research employing multilevel Monte Carlo simulation demonstrates that modelling component availability can support distribution reliability evaluation while reducing computational requirements associated with conventional simulation techniques (Nazmul Huda & Zivanovic, 2019).

Monte Carlo simulation is particularly valuable for manufacturing networks containing several interconnected feeders, alternative supply arrangements, and equipment with uncertain failure characteristics. Sequential approaches reproduce chronological operating conditions, allowing analysts to represent component outages, repair activities, and changing electrical demand. Research on multi-state distribution systems demonstrates that accelerated Monte Carlo methods can accommodate

complex microgrid operating conditions while estimating reliability performance under different system states (Yan et al., 2018).

The integration of photovoltaic generation, energy storage, and standby electricity sources introduces additional considerations into reliability modelling. Generation availability, storage capacity, switching arrangements, and source intermittency influence the ability of industrial installations to maintain essential loads. Markov-based reliability models provide a means of representing transitions between operating and failed states, supporting assessment of distributed generation and storage contributions to service continuity (Adefarati & Bansal, 2017).

Restoration-related reliability assessment should additionally account for temporary increases in electrical demand following prolonged interruptions. Simultaneous restarting of industrial motors, compressors, and auxiliary equipment may produce substantial current demands that complicate feeder restoration. Research incorporating cold-load pickup behaviour demonstrates the importance of considering restoration sequences, protection constraints, and load uncertainty when evaluating distribution-system reliability (Al-Nujaimi, Abido & Al-Muhaini, 2018).

Evidence from South Africa further demonstrates the practical value of reliability-based assessment. Research involving the Soweto distribution network applied interruption indices and component performance characteristics to identify opportunities for improving feeder reliability and reducing interruption consequences (Montso & Pretorius, 2018).

Similarly, investigations in Gauteng employed historical outage information and probabilistic reliability analysis to identify distribution-system vulnerabilities and support predictive maintenance decisions (Choma, Pretorius & Marnewick, 2019). For Nigerian manufacturing facilities, combining these assessment methods with equipment-specific failure records, protection operating histories, and production interruption data can provide a more comprehensive basis for evaluating reliability performance, prioritising maintenance investments, and identifying weaknesses in low-voltage protection coordination.

4. ELECTRICAL FAULT ANALYSIS AND SYSTEM VULNERABILITIES

Electrical fault analysis is essential for evaluating the operational vulnerability and protective performance of low-voltage distribution systems in Nigerian manufacturing facilities. Industrial networks experience electrical disturbances arising from insulation deterioration, conductor damage,

excessive loading, defective connections, and equipment malfunction. These conditions can produce phase-to-phase faults, three-phase short circuits, earth faults, and intermittent arcing. Fault magnitude and duration depend on network impedance, transformer characteristics, earthing arrangements, and connected generation sources. Consequently, systematic fault assessment must establish prospective short-circuit currents, vulnerable equipment locations, and the effectiveness of protective-device operation. Research on distribution fault identification demonstrates that current-signal analysis using wavelet transformations can distinguish fault characteristics and support the identification of affected phases and locations (Authafa & Abdul-Hassan, 2018).

In Nigerian manufacturing facilities, particular vulnerabilities may arise from ageing switchgear, inadequate preventive maintenance, poorly terminated conductors, and modifications undertaken without updated electrical studies. Faults occurring within main distribution boards or essential production feeders can interrupt multiple industrial processes, increasing equipment damage and operational downtime. Grounding-system performance is especially important because inappropriate earthing arrangements can increase hazardous touch potentials and compromise earth-fault protection. Research examining grounding-system optimisation in emerging electricity markets emphasises the importance of soil characteristics, electrode configuration, installation constraints, and electrical safety requirements in achieving acceptable grounding performance (Adeniji et al., 2020).

Accurate fault-location techniques provide an additional mechanism for reducing network vulnerability. Traditional fault investigations frequently depend on circuit inspection and successive isolation procedures, which can prolong restoration activities. A Nigerian investigation employing impedance-based calculations and fuzzy inference demonstrated the potential for improving fault-distance estimation in distribution networks. Such techniques provide a methodological basis for developing more efficient fault investigation procedures where appropriate electrical measurements and network parameters are available (Okoli et al., 2020).

Advanced monitoring approaches further strengthen fault detection through continuous assessment of voltage and current behaviour. Research employing phasor measurement units and state estimation demonstrates that electrical measurements can identify faulted sections within active distribution networks, potentially improving diagnostic accuracy where distributed generation complicates conventional fault-location methods (Gholami et al., 2020).

Signal-processing approaches offer complementary capabilities for identifying fault origins. Analysis of symmetrical-component waveform energy can distinguish disturbance locations using measured voltage variations, supporting faster identification of affected distribution sections and more targeted maintenance interventions (Moraes, Lovisolo & Monteiro, 2018).

The increasing availability of digital monitoring equipment also creates opportunities for automated asset-condition assessment. Research applying deep neural networks to low-voltage cable fault records demonstrates the potential to distinguish failures associated with cable sections, joints, and terminations. These capabilities are relevant to industrial facilities seeking to improve maintenance prioritisation and reduce repeated equipment failures (Mastroleo et al., 2018).

Fault frequency characteristics provide another diagnostic perspective. Frequency-component analysis can assist in identifying faulted sections, particularly where complex network configurations make conventional identification difficult. Such techniques may complement protective-device records and operational measurements when investigating recurring industrial distribution faults (Gord et al., 2019).

Evidence from South Africa additionally establishes the importance of limiting energy exposure during electrical faults. Research examining distribution recloser placement demonstrated that protection settings and fault-energy exposure influence equipment damage and network reliability. This highlights the need for Nigerian manufacturers to evaluate fault-clearing duration alongside prospective fault magnitude when coordinating protective devices (Thomas et al., 2019).

Table 1. Illustrative electrical fault types, vulnerabilities, and assessment priorities in low-voltage manufacturing distribution systems

Electrical fault or vulnerability	**Typical industrial causes**	**Potential consequences**	**Recommended assessment**
Three-phase short circuit	Busbar contact, insulation breakdown	Severe thermal and mechanical stresses	Maximum fault-current calculation; interrupting-capacity verification
Phase-to-phase fault	Cable damage, conductor insulation failure	Equipment damage and feeder interruption	Short-circuit analysis; protective-device coordination

Electrical fault or vulnerability	**Typical industrial causes**	**Potential consequences**	**Recommended assessment**
Earth fault	Damaged insulation, exposed conductive parts	Electric shock risk, fire, circuit disconnection	Earth-fault loop impedance; earthing and disconnection verification
Overloaded feeders	Production expansion, excessive connected demand	Conductor overheating, insulation deterioration	Load profiling; cable ampacity and breaker-setting assessment
High-resistance connections	Loose terminals, corrosion, poor maintenance	Localised heating, potential arcing	Thermal inspection; contact-resistance testing
Intermittent arcing	Defective joints, deteriorating switchgear	Fire risk, repeated disturbances	Waveform analysis; targeted equipment inspection
Generator-related fault variations	Utility-generator switching, multiple supply sources	Changed fault levels, loss of selectivity	Source-specific fault calculations; coordination review
Protective-device miscoordination	Incorrect settings, unsuitable device ratings	Unnecessary upstream tripping and wider outages	Time-current curve analysis; selectivity verification

Source: Author's synthesis of engineering fault mechanisms and assessment priorities. The table is illustrative and does not represent measured fault statistics from Nigerian manufacturing facilities.

The combined assessment of fault characteristics, vulnerable components, earthing performance, and protection operating behaviour provides a technical basis for identifying weaknesses in industrial distribution networks. For Nigerian manufacturing facilities, particular emphasis should be placed on source-dependent short-circuit calculations, documented fault histories, equipment-condition inspections, and verification of protective selectivity under both utility and standby-generation operating conditions.

5. PROTECTION DEVICE SELECTION AND COORDINATION STRATEGIES

Protection device selection and coordination constitute essential engineering requirements for maintaining electrical safety, operational continuity, and fault isolation within low-voltage distribution systems in Nigerian manufacturing facilities. Industrial protection arrangements typically incorporate miniature circuit breakers, moulded-case circuit breakers, air circuit breakers, fuses, residual-current devices, and electronic protective relays. Their selection requires consideration of rated current,

prospective short-circuit capacity, conductor thermal limits, fault sensitivity, and operating characteristics. Effective coordination ensures that the protective device nearest a fault disconnects the affected circuit while upstream devices maintain supply to unaffected production equipment. Nigerian investigations demonstrate that properly positioned sectionalising devices can reduce interruption duration and improve distribution-system reliability, provided their deployment reflects actual network operating conditions (Nweke, Gusau & Isah, 2020).

Protective selectivity depends substantially on appropriate relationships between device pickup currents and operating times. Inverse-time overcurrent protection permits higher fault currents to produce shorter operating times, while coordinated upstream and downstream settings establish the required discrimination. Research on interconnected distribution networks demonstrates that systematic optimisation of relay pickup currents and time multiplier settings can reduce fault-clearing duration while satisfying coordination constraints (Damchi et al., 2018).

In industrial installations, coordination studies must account for transformer impedance, motor starting currents, cable characteristics, and variations in available fault current. Manufacturing equipment frequently experiences substantial starting currents, making inappropriate instantaneous-trip settings a potential source of unnecessary disconnection. Protection strategies based on time-current-voltage characteristics have demonstrated improved relay operating performance, particularly in distribution systems containing multiple generation sources and changing electrical conditions (Saleh et al., 2015).

The integration of standby generators, photovoltaic systems, and energy storage introduces additional coordination challenges. These sources can modify fault-current magnitude and direction, potentially invalidating protection settings established for utility-only operation. Nigerian research involving optimally located distributed generation demonstrates that relay coordination intervals and operating characteristics can change with generation penetration, highlighting the importance of evaluating protection performance under alternative network configurations (Okorie et al., 2019).

Adaptive protection provides an important response to changing industrial distribution conditions. Unlike fixed-setting arrangements, adaptive systems modify protective characteristics according to network operating modes, source availability, or switching configurations. Research examining multiple-source meshed networks demonstrates that dual-setting directional overcurrent protection can

improve discrimination and reduce unnecessary operating delays under varying fault directions (Yazdaninejadi et al., 2017).

Protection coordination may also be strengthened through computational optimisation. Hybrid particle swarm optimisation and gravitational search techniques have been investigated for determining relay settings that minimise operating times while maintaining primary and backup coordination. Such approaches provide useful analytical methods for facilities containing interconnected feeders and multiple electricity sources (Srivastava et al., 2016).

Where distributed generation causes excessive fault-current contributions, fault current limiters can provide additional coordination support. Research undertaken in Egypt demonstrates that optimally locating and sizing these devices can preserve overcurrent relay coordination under different generation arrangements, although practical application requires consideration of equipment costs and network characteristics (Elmitwally et al., 2015).

Finally, coordination strategies must account for operational stability and the consequences of delayed fault isolation. Research incorporating transient stability constraints demonstrates that protection optimisation should consider both selective fault clearance and the ability of interconnected generation sources to remain stable during disturbances (Yazdaninejadi & Nazarpour, 2019). For Nigerian manufacturing facilities, dependable protection therefore requires coordinated device selection, verified fault calculations, manufacturer-specific discrimination studies, and periodic assessment following equipment modifications.

Table 2. Illustrative protection devices, selection criteria, and coordination strategies for low-voltage manufacturing facilities

Protection device	**Typical industrial application**	**Principal selection criteria**	**Coordination strategy**
Miniature circuit breaker (MCB)	Lighting, control circuits, small auxiliary loads	Rated current, trip characteristic, breaking capacity	Verify downstream selectivity using manufacturer data
Moulded-case circuit breaker (MCCB)	Production feeders, motor distribution, subpanels	Frame rating, adjustable trip settings, interrupting capacity	Coordinate overload, short-time, and instantaneous functions
Air circuit breaker (ACB)	Main low-voltage switchboards and incomers	Rated current, fault interruption capability, short-time withstand	Apply appropriate time grading and selective short-circuit protection

Protection device	**Typical industrial application**	**Principal selection criteria**	**Coordination strategy**
High-rupturing-capacity (HRC) fuse	Motor branches, equipment feeders, semiconductor protection where specified	Fuse class, utilisation category, melting characteristics, let-through energy	Verify fuse-to-fuse or fuse-to-breaker discrimination
Residual-current device (RCD)	Circuits requiring additional electric-shock or earth-leakage protection	Rated residual operating current, RCD type, operating time	Coordinate upstream and downstream residual-current protection
Electronic overcurrent relay	Industrial feeders and generator-associated circuits	Pickup range, time-current curve, measurement accuracy	Verify primary and backup operation across applicable fault levels
Directional overcurrent relay	Multi-source or interconnected distribution arrangements	Directional sensitivity, fault-current range, operating time	Coordinate directional settings for different source configurations
Differential protection	Transformers, busbars, and selected critical equipment	Protection-zone boundaries, current transformer performance, sensitivity	Maintain zone-selective protection with appropriate external-fault stability

Source: Author-developed synthesis of low-voltage protection functions and engineering coordination principles. Device applicability and selectivity must be confirmed through project-specific calculations, applicable standards, and manufacturer documentation. The table is illustrative rather than an approved protection schedule.

For application within Nigerian manufacturing facilities, the selection and coordination principles presented in Table 2 should be evaluated against actual network configurations, transformer capacities, conductor specifications, and fault-current conditions. Particular consideration should be given to low-fault-current operation under standby generation, maximum fault duties under utility supply, and the coordination of main incomers with downstream production feeders. These assessments are necessary to establish whether proposed protection arrangements provide adequate sensitivity, discrimination, and equipment protection without compromising essential manufacturing operations.

6. POWER QUALITY CHALLENGES AND EQUIPMENT RELIABILITY

Power quality constitutes a critical determinant of equipment performance and operational reliability within low-voltage electrical distribution systems serving Nigerian manufacturing facilities. Industrial installations require stable voltage magnitude, frequency, waveform characteristics, and phase balance to

sustain continuous production. However, voltage sags, harmonic distortion, transient overvoltages, and supply unbalance can compromise electrical equipment performance without necessarily causing sustained power interruptions. These disturbances are particularly consequential in manufacturing environments containing programmable controllers, variable-frequency drives, automated machinery, and sensitive electronic equipment. International testing requirements recognise that equipment operating below 1,000 V may malfunction during short-duration voltage reductions, necessitating systematic evaluation of voltage-sag immunity and equipment ride-through capabilities (IEEE, 2017).

Voltage sags represent a significant operational concern because relatively brief disturbances can interrupt interconnected manufacturing processes. Faults occurring within upstream distribution networks may propagate voltage depressions into industrial facilities, affecting equipment even when protective devices do not disconnect the incoming supply. Investigations involving industrial distribution circuits demonstrate that voltage-sag severity, duration, and equipment sensitivity substantially influence production interruptions. Consequently, evaluating voltage disturbances requires consideration of both electrical characteristics and the operational requirements of connected manufacturing equipment (Arias-Guzmán et al., 2017).

Harmonic distortion presents another reliability challenge, particularly where manufacturing installations operate nonlinear loads such as rectifiers, welding equipment, electronic drives, and switched-mode power supplies. Harmonic currents can increase transformer losses, conductor heating, and neutral-current loading while contributing to equipment malfunction and protection-related complications. Nigerian research examining the Abuja Steel Mill Feeder established the importance of identifying harmonic orders and modelling distorted electrical waveforms before implementing mitigation measures within industrial supply networks (Nwohu et al., 2017).

Voltage unbalance similarly affects three-phase induction motors widely employed in industrial pumping, ventilation, compression, and material-handling operations. Unequal phase voltages produce negative-sequence currents, increasing thermal stress and potentially reducing motor efficiency and service life. Research investigating induction motor performance under unbalanced supply conditions demonstrates that variations in voltage magnitude and phase angle influence operating current, electromagnetic torque, losses, and power factor. These relationships emphasise the importance of maintaining suitable phase balance within manufacturing distribution networks (Dekhandji, Refoufi & Bentarzi, 2017).

Equipment reliability also depends on operating efficiency and appropriate control strategies. Intelligent control arrangements can regulate equipment demand, minimise unnecessary operating cycles, and improve energy management. Research examining air-conditioning systems demonstrates the potential of adaptive and predictive control techniques to enhance equipment operating efficiency, providing relevant principles for managing electrically driven auxiliary systems within industrial facilities (Sunday et al., 2019).

Power quality mitigation requires coordinated engineering interventions rather than isolated equipment replacement. Active power filters offer a means of compensating harmonic currents and reactive power demands associated with nonlinear electrical loads. Experimental investigations demonstrate that appropriately controlled filtering systems can reduce waveform distortion and improve electrical power characteristics under varying operating conditions (Kashif et al., 2018).

The performance of standby generation systems also warrants consideration because manufacturing facilities frequently depend on generators during utility interruptions. Harmonic-producing loads can affect generator output quality, particularly where generating capacity is limited relative to nonlinear demand. Research involving synchronous generators demonstrates that active filtering can improve output current characteristics and reduce harmonic distortion, supporting more dependable generator operation (Abu-Jalala et al., 2018).

From an African perspective, research undertaken in South Africa establishes that voltage disturbances can impose measurable economic consequences on electricity consumers. Stochastic assessment of distributed generation demonstrates that supplementary generating resources can reduce expected voltage-sag-related losses under specified network conditions (Mbuli et al., 2016). For Nigerian manufacturing facilities, these findings reinforce the importance of combining continuous power quality monitoring, appropriate equipment immunity, harmonic mitigation, balanced feeder loading, and carefully coordinated protection arrangements to sustain reliable low-voltage distribution performance.

7. RELIABILITY IMPROVEMENT STRATEGIES FOR NIGERIAN MANUFACTURING FACILITIES

Improving the reliability of low-voltage electrical distribution systems in Nigerian manufacturing facilities requires an integrated approach encompassing infrastructure modernisation, preventive

maintenance, protection coordination, and operational monitoring. Industrial reliability improvement should prioritise identifying vulnerable feeders, replacing deteriorated equipment, and establishing systematic fault-response procedures. Particular emphasis is required where ageing switchgear, inadequate feeder capacity, and prolonged restoration activities expose manufacturing operations to repeated interruptions. Nigerian research on distribution-system performance demonstrates that automated fault detection and communication arrangements can improve fault identification and support faster restoration of electricity supply (Akinwumi & Komolafe, 2011).

Distribution network reconfiguration provides an important strategy for reducing electrical vulnerabilities and improving supply continuity. Appropriate switching arrangements can isolate defective network sections while maintaining electricity supply to unaffected production areas. Research examining distribution reconfiguration establishes that strategically modifying feeder connections can reduce technical losses, improve load distribution, and strengthen reliability without requiring extensive infrastructure replacement (Sultana et al., 2016).

Reliability improvement should also incorporate load prioritisation and selective redundancy. Manufacturing facilities contain equipment with different operational criticalities, making it necessary to distinguish essential production machinery from interruptible auxiliary loads. Optimisation research demonstrates that strategic placement of switching devices and alternative supply connections can improve service continuity under equipment-failure conditions while considering investment requirements (Vasudevan & Sinha, 2018).

The integration of standby generators and renewable energy installations further requires coordinated protection assessment. Changes in generation capacity, fault-current contribution, and network configuration may alter protective-device operating characteristics. Research on distributed generation demonstrates that incorporating protection coordination constraints into network reconfiguration and generation-sizing decisions can improve technical compatibility and operational dependability (Rahim, Mokhlis & Bakar, 2019).

Electrical efficiency represents another essential consideration. Network optimisation can reduce excessive feeder loading, improve voltage profiles, and minimise technical losses associated with inefficient distribution configurations. Research involving Nigerian and Ethiopian institutions demonstrates that optimal switching arrangements can improve voltage regulation and distribution

performance, providing relevant engineering principles for industrial electrical network planning (Salau, Gebru & Bitew, 2020).

Evidence from Ethiopia additionally highlights the importance of evaluating proposed interventions through measurable reliability indicators. Distribution reconfiguration studies demonstrate that comparing interruption frequency, outage duration, and expected energy not supplied can support economically justified improvement decisions (Anteneh & Khan, 2019).

Sustainable reliability improvement also depends on workforce competence and organisational preparedness. Structured technical training, defined maintenance responsibilities, and systematic performance evaluation can strengthen operational capability across complex industrial activities (Falemi, Akhigbe & Akin-Oluyomi, 2020). Within Nigerian manufacturing facilities, these considerations support the adoption of documented preventive maintenance schedules, periodic protection-setting verification, equipment-condition monitoring, and reliability-based investment priorities to minimise avoidable electrical failures and sustain production continuity.

8. CONCLUSION

This review provides a comprehensive examination of the technical and operational factors influencing electrical reliability, fault management, and protective-device coordination within Nigerian manufacturing facilities. By evaluating distribution architectures, reliability assessment methodologies, electrical fault characteristics, protection strategies, and power quality challenges, the study has addressed its objectives and established an integrated framework for understanding industrial electrical system performance. The findings demonstrate that dependable electricity distribution requires more than adequate power availability; it also depends on appropriate system design, selective fault isolation, equipment integrity, and effective maintenance practices.

The review identifies ageing infrastructure, inadequate protection coordination, feeder overloading, voltage disturbances, and insufficient maintenance as significant potential threats to manufacturing continuity. It further establishes that conventional distribution arrangements may become increasingly vulnerable when standby generators, renewable energy systems, and interconnected production loads introduce changing fault-current conditions. Reliability assessment techniques, including interruption indices, component failure analysis, and probabilistic modelling, provide valuable approaches for identifying vulnerabilities and evaluating improvement opportunities. Nevertheless, limited facility-

specific empirical evidence remains a substantial constraint on accurately characterising electrical reliability across Nigerian manufacturing installations.

Accordingly, manufacturing operators should prioritise comprehensive electrical system audits, updated short-circuit calculations, protective-device discrimination studies, and systematic equipment condition monitoring. Preventive maintenance programmes should incorporate periodic testing of circuit breakers, grounding arrangements, and critical distribution components. Investments in feeder redundancy, power quality monitoring, and appropriately coordinated alternative energy sources should be guided by operational criticality and economic feasibility. Furthermore, continuous technical training and reliable documentation of electrical incidents are essential for strengthening maintenance effectiveness and organisational preparedness.

Future research should emphasise field-based reliability assessments, comparative protection coordination studies, and quantitative evaluations of equipment failure patterns across diverse manufacturing environments. Integrating operational measurements with analytical modelling would enable more robust assessment of intervention effectiveness. Ultimately, improving industrial electrical reliability demands coordinated engineering investment, evidence-based maintenance decisions, and sustained institutional commitment to safer, more resilient manufacturing operations nationwide.

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